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Do High-Velocity Clouds *Really* Fuel Galactic Star Formation?

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Abstract. Tantalizing evidence has been presented supporting the suggestion that a large population of extragalactic gas clouds permeates the Local Group, a population which has been associated with the Galactic High-Velocity Clouds (HVCs). We comment on both the strengths and weaknesses of this suggestion, informally referred to as the Blitz/Spergel picture. Theoretical predictions for the spatial and kinematic distributions, metallicities, distances, and emission properties of Blitz/Spergel HVCs will be confronted with extant observational data.

1. Introduction

Simulations of the Local Group's formation (Klypin et al. 1999) predict that an order of magnitude more satellites should be associated with the Milky Way and M31 than are actually observed. This discrepancy is a significant challenge to hierarchical clustering scenarios. An intriguing suggestion as to the whereabouts of the "missing" satellites is provided by the Local Group infall model of Blitz et al. (1999), who speculate that a large fraction of the classical ensemble of HVCs are these Local Group building blocks. The continuing infall of the HVCs onto the disk of the Galaxy would then provide the bulk of the fuel necessary to maintain ongoing star formation.

HVCs are ubiquitous ($\sim$20% sky covering fraction) clouds seen in HI emission, whose velocities are incompatible with simple models of Galactic rotation. Because the majority of their distances are effectively unconstrained, rampant speculation exists as to their exact nature and origin, ranging from solar metallicity Galactic fountain gas ($d \lesssim 10\,$kpc and $Z\sim Z_\odot$), to Magellanic Cloud tidal debris ($d \lesssim 50\,$kpc and $Z\gtrsim 0.25\,Z_\odot$), to the Blitz/Spergel Local Group formation remnants ($d \gtrsim 400\,$kpc and $0.0\lesssim Z\lesssim 0.1\,Z_\odot$).

The fact that each scenario makes specific predictions regarding the distance and metallicity for the "typical" HVC means that, in principle, the above models could be distinguished from one another wth appropriate observations. In practice, the definitive observational discriminant has been difficult to obtain.

2. Distances

The cleanest discriminant between the competing HVC models is that of their distance. If it could be shown that the majority of HVCs reside in the Galactic halo, as opposed to being distributed throughout the Local Group, one could sound the death knell for the Blitz/Spergel model. Unfortunately, direct distance determinations for HVCs are few and far between; to set a useful upper limit requires a suitably bright background halo star of known distance to lie directly behind a high HI column density HVC. The dearth of catalogued blue horizontal branch stars and early subdwarfs in the outer halo (RR Lyrae stars can sometimes be employed, in a pinch) is one immediate problem; those bright enough to obtain high S/N, high-resolution spectra (to actually search for HVC absorption features) are rarer still. Non-detections (both for foreground and background probes) are more difficult to interpret, as fine-scale HI structure may conspire to make the probe "miss" any intervening HI.

To date, there are only five HVCs for which either an upper limit or distance bracket exists. As Table 1 shows, of these five HVCs none is consistent with an intra-Local Group residence, as might be expected under the Blitz/Spergel picture. An ongoing attempt to detect Complex WD in absorption towards a distant halo RR Lyrae star may soon add a sixth entry to Table 1 (Comeron 2000). A few other HVCs have solid lower distance limits, but they do not provide any discriminant between halo and Local Group residence (being only $\gtrsim$1−5 kpc). These are therefore not reported here.

Table 1. HVC Distances: Upper Limits or Distance Brackets

HVC	Distance (kpc)	Reference
100− 7+110	<1	Bates et al. (1991)
Complex M	<4	Ryans et al. (1997)
328−16+100	<11	Sembach et al. (1991)
Complex A	4−10	van Woerden et al. (1999)
279−33+120	<50	Richter et al. (1999)

The background stellar probe technique described above is virtually impossible to apply to any potential Local Group HVC at $d \gtrsim 400$ kpc. Perhaps the most promising method for attempting to prove an HVC truly lies at ∼Mpc distances lies in the detection of the tip of the red giant branch in any putative stellar population associated with the HVC (Grebel et al. 2000).

Recently, Combes & Charmandaris (2000) have shown that both the Wakker & Schwarz (1991) and Braun & Burton (1999) HVCs (at $1'$ and $30'$ resolution, respectively) follow closely the size-linewidth relation defined by Galactic molecular clouds, *provided that their mean distances are ∼20 kpc.* This is *indirect* evidence against the Blitz/Spergel picture, but concerns regarding the use of the size-linewidth technique as a distance determinator must be heeded (Wakker & van Woerden 1997; § 4.1).

3. Kinematics and Spatial Deployment

Both Blitz et al. (1999) and Braun & Burton (1999) have used the fact that the dispersion $\sigma_{\rm LSR}$ in the HVC distribution relative to $v_{\rm LSR}$ is greater than the dispersion $\sigma_{\rm GSR}$ relative to $v_{\rm GSR}$ or $v_{\rm LGSR}$ as support for preferring the Galactic and Local Group standards of rest, over the local standard of rest. They use this as indirect support for an extragalactic origin for many HVCs.

It should be stressed that, while $\sigma_{\rm GSR} < \sigma_{\rm LSR}$ *is* a necessary condition for the Blitz/Spergel picture, it does *not* constitute sufficient proof. Any model that predicts a sinusoidal $v_{\rm LSR}$ vs. Galactic longitude distribution, necessarily satisfies the same $\sigma_{\rm GSR} < \sigma_{\rm LSR}$ condition, a wholly underappreciated fact. Specifically, $\sigma_{\rm GSR} < \sigma_{\rm LSR}$ for *all* Local Group infall *and* Galactic fountain *and* Magellanic Stream disruption models. In addition, there is a significant selection effect at play in these $\sigma_{\rm GSR}$ vs $\sigma_{\rm LSR}$ comparisons in that $|v_{\rm LSR}| \lesssim 100\,{\rm km\,s^{-1}}$ HI is not included in the $\sigma_{\rm GSR} \Rightarrow \sigma_{\rm LSR}$ conversion. Any effect this "missing" gas might have upon the resulting distribution was neglected by Blitz et al. (1999) and Braun & Burton (1999).

The superposition of Wakker's (1990; Ch. 5) Galactic fountain and Magellanic Stream models results in an HVC flux distribution indistinguishable from that observed. Specifically, sum Figures 9(b) and 9(d) of Ch. 5 in Wakker (1990) and contrast with Figure 5 of Ch. 2. Not only is the flux distribution reproduced, but so are many secondary signatures, including the asymmetry in the velocity extrema (Blitz et al. 1999; § 5.2.3). To be fair, it should be noted that the spatial deployment of the HVCs (in the $\ell - b$ Aitoff projection) in Wakker's Galactic fountain + Magellanic Stream model (top panels of Fig. 3 and 8 of Ch. 5 of Wakker 1990) appears inferior to that of the Blitz et al. (1999; Fig. 13) model. New Galactic fountain models from de Avillez (2000) may reduce this discrepancy.

4. Metallicities

High spectral resolution and high S/N ultraviolet spectra taken with spectrometers aboard HST and FUSE have enabled major advances in quantifying the distribution of HVC metallicities. Preferred atomic lines for such abundance analyses include those of SII and OI (α-elements, minimal dependency upon ionization corrections, relatively insensitive to dust depletion); other popular lines include those of FeII, SiII, and MgII (albeit subject to large depletion corrections) and NI (dominated by secondary production at low metallicities, however).

Regardless of atomic species considered, *many* abundance determinations are susceptible to uncertain dust depletion corrections, *most* are susceptible to uncertain ionization corrections, and *all* are subject to (potentially considerable) spatial resolution uncertainties. The latter cannot be emphasized strongly enough. The absorption line is probing sub-arcsecond scales in the intervening HVC gas, while the 21cm HI is probing a scale 2−3 orders of magnitude greater! Substantial systematic uncertainties are typically incorporated into the final quoted result to reflect this "resolution" uncertainty, but one can never be certain that a pathological case has not been encountered.

Recall from § 1 that in the Blitz/Spergel picture, metallicities of the order $\lesssim 0.1\,{\rm Z}_\odot$ are to be expected (but not necessarily primordial), while under a Galactic fountain scenario values of $\sim{\rm Z}_\odot$ should be more prevalent. Magellanic Cloud debris might be expected to lie in the $\sim 0.2-0.4\,{\rm Z}_\odot$ regime. Table 2 lists eight recent HVC metallicity determinations; it is by no means complete, but it does provide a representative sample.

Table 2. High-Velocity Cloud Abundances

HVC	Abundance	Reference
Complex C	$0.1-0.4\,\mathrm{S/H}_\odot$	Wakker et al. (1999); Gibson et al. (2001a)
Complex WB	$\gtrsim 0.1\,\mathrm{Ca/H}_\odot$	Robertson et al. (1991)
287+22+240	$0.3\,\mathrm{S/H}_\odot$	Lu et al. (1998)
Magellanic Stream	$0.3\,\mathrm{S/H}_\odot$	Gibson et al. (2000)
225−83−200	$\gtrsim 0.3\,\mathrm{Fe/H}_\odot$	Gibson et al. (2001b)
279−33+120	$\gtrsim 0.5\,\mathrm{Fe/H}_\odot$	Richter et al. (1999)
258−39+232	$\gtrsim 0.6\,\mathrm{Si/H}_\odot$	Sahu & Blades (197)
100− 7+110	$0.7\,\mathrm{O/H}_\odot$	Bates et al. (1990,1991)

An immediate conclusion to be drawn from Table 2 is that, *to date*, no HVC shows unequivocal evidence for $Z<0.1\,Z_\odot$ (Blitz/Spergel). Conversely, no HVC shows unequivocal evidence for $Z>1.0\,Z_\odot$ (Galactic fountain), an interesting conundrum! Future HST/STIS and FUSE analyses are sorely needed, particularly in light of the fact that the anti-Local Group barycentre clouds, where the Blitz/Spergel picture predicts an excess of intra-Local Group HVCs, have yet to be sampled in UV absorption.

According to simple models of Galactic chemical evolution with gas infall (Tosi 1988), $Z_{\rm inf}$ must be $\lesssim 0.1\,Z_\odot$; for $Z_{\rm inf} > 0.15$, the resulting stellar population distribution violates the present-day Galactic disk constraints. Table 2 would then imply that the majority of HVCs are not representative of the class of infalling gas clouds invoked by theorists to explain the G-dwarf problem (the status of Complex C is still being debated at this time).

While not listed in Table 2, HVC 125+41−207 deserves special mention. This HVC has received attention from Braun & Burton (1999) owing to its exceptionally narrow core HI linewidth ($\lesssim 2\,\mathrm{km\,s^{-1}}$). An indirect argument based upon thermal and pressure characteristics suggests that the distance to this HVC is of the order $\sim$700 kpc (the quoted distance is based upon an unpublished modification of the Wolfire et al. 1995 model, and so a formal uncertainty in this number is not yet available). Very low abundances have been claimed for this HVC based upon MgII $\lambda\lambda$2796,2803 derived from the HST/GHRS spectrum of Bowen & Blades (1993) and Bowen et al. (1995) along the line of sight to the background AGN Mrk 205. The former group found W_λ(MgII 2796)=76±12 mÅ and W_λ(MgII 2803)=46±17 mÅ, while the latter found W_λ(MgII 2796)=169±28 mÅ and W_λ(MgII 2803)=73±30 mÅ, based upon the same spectrum; the source of the discrepancy is not stated. Our conservative analysis of their dataset yields W_λ(MgII 2796)=130±40 mÅ and W_λ(MgII 2803)=90±40 mÅ. A *b*-value of $6\pm1\,\mathrm{km\,s^{-1}}$ was found by all groups. Constructing curves of growth, our analysis implies a MgII abundance (68% c.l.) of (0.03−0.19) $\mathrm{Mg/H}_\odot$. Dust depletion similar to that seen in the Galactic halo clouds would increase this value by a factor of 3−4. Unfortunately, the low S/N FUSE spectrum for Mrk 205 has (thus far) been unable to shed new light on the metallicity of HVC 125+41−207, but a scheduled HST/STIS programme (PID#8625) should clarify the situation.

5. The Magellanic Stream

Special mention should be made of the most spectacular of HVCs, the Magellanic Stream (MS), an $\sim$1000 deg^2 HI feature trailing the Magellanic Clouds. The MS is the one HVC for which we know the origin: the Clouds themselves. What remains controversial is the exact mechanism by which this gas was extracted from said Clouds: tides or ram pressure stripping? The key discriminants between the two scenarios are: (i) the prediction of a leading counterpart to the trailing Stream (tidal models); and (ii) the tip of the Stream (MS IV$\rightarrow$MS VI) being 2−3× further away in the case of tides, than in the case of drag. A consequence of (ii) is the prediction that, in the mean, the intensity of Hα emission I(Hα) from the Stream should decrease (increase) the further one moves down-Stream, under the tidal (drag) scenario [under the inherent assumption that I(Hα) is driven primarily by photo-ionization, as opposed to collisional ionization (c.f. Weiner et al. 2001)].

The extant observational data on the Stream favours the tidal scenario, although there are admittedly one or two weak links:

- existence of Leading Arm Feature (LAF) $\Rightarrow$ tides (Putman et al. 1998)
- metallicity of Leading Arm HVC 287+22+240 $\Rightarrow$ tides (Lu et al. 1998)
- *if* I(Hα)$_{\rm MSV,VI}$<I(Hα)$_{\rm MSII}$ $\Rightarrow$ tides
- I(Hα)$_{\rm LAF}$<<I(Hα)$_{\rm MS}$ $\Rightarrow$ not tides (Bland-Hawthorn et al. 2001)
- stars not observed in MS $\Rightarrow$ tides *or* drag (Yoshizawa 1998; Mihos 2001)
- star streams in vicinity of LMC $\Rightarrow$ tides (Majewski et al. 1999)
- *if* N$_{\rm HII,disk}$(65 kpc)$\lesssim$10^{19} cm^{-2} *or if* n$_{\rm halo}$(50 kpc)$\neq$(5±1)×10^{-5} cm^{-3} $\Rightarrow$ not Moore & Davis (1994) drag

6. Conclusions

Perhaps the most important conclusion to take from the study of HVCs is that they are *not* all the same beasts. To categorize all HVCs as due to a fountain (Galactic waste) or infalling remnants of the Local Group's formation (Galactic fuel) is doomed to failure from the start. No doubt there are a plethora of origins scattered about the HVC family tree. What can be concluded is that (to date) there is no unequivocal evidence for the existence of intra-Local Group HVCs, based upon limited distance, metallicity, and optical emissivity arguments. Concerning the latter, neither Weiner et al. (2001) nor Tufte et al. (2001) have thus far observed an HVC consistent with the I(Hα) predictions of the Blitz/Spergel model (c.f. Bland-Hawthorn et al. 2001). On the other hand, neither is there unequivocal evidence for the existence of Z$\gtrsim$Z$_\odot$ HVCs, as might be expected for a Galactic fountain origin (intermediate-velocity clouds on the other hand do occasionally show Z$\sim$Z$_\odot$, but that is a story left for another day).

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